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Long-term changes in extreme temperatures and precipitation in Spain

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Resum

La creació de les bases de dades de temperatura i precipitació diàries anomenades, respectivament, Spanish Daily Adjusted Temperature Series (SDATS) i Spanish Daily Adjusted Precipitation Series (SDAPS), en el marc del projecte finançat per la Comissió Europea EMULATE (*E*uropean and North Atlantic daily to *MUL*tidecadal clim*ATE* variability), ha permès als autors analitzar el canvi a llarg termini que s'ha produït en el comportament anual dels extrems climàtics a l'Espanya peninsular durant el període 1901-2005. El conjunt de procediments desenvolupats pels autors per tal de crear registres homogenis de la temperatura i de la precipitació diàries són descrits de manera breu abans d'analitzar els canvis observats en l'ocurrència d'extrems climàtics. S'han utilitzat els indicadors següents per a dur a terme aquest estudi: excedències dels percentils inferiors i superiors de les temperatures màximes (T_{max}) i mínimes (T_{min}) diàries, excedències de la precipitació diària per sobre dels percentils 95è i 99è, l'índex simple d'intensitat diària (SDII) i els indicadors d'1 i 5 dies amb la precipitació més alta de l'any. Tant l'anàlisi dels percentils superiors de les temperatures com la dels inferiors mostren que s'ha produït un escalfament important sobre l'Espanya peninsular al llarg del segle XX, i que aquest ha estat més important en les temperatures màximes que en les temperatures mínimes. No obstant això, aquest patró presenta un lleuger canvi en el període més recent d'escalfament, en el qual la tendència d'ambdues variables presenta valors similars. Els canvis en els indicadors pluviomètrics no són tan clars com els estimats per la temperatura, però s'ha detectat una tendència cap a l'ocurrència de pluges més intenses.

Paraules clau: canvi tèrmic i pluviomètric extrem, distribució diària, indicadors de temperatura i precipitació extremes, Espanya

Abstract

The development of the Spanish daily adjusted temperature series (SDATS) and the Spanish daily adjusted precipitation series (SDAPS) datasets in the framework of the European Community (EC)-funded project EMULATE (European and North Atlantic daily to MULtidecadal climATE variability) enabled the assessment of long-term annual changes of extreme temperature and precipitation indices over peninsular Spain for the period 1901–2005. Within this framework, a set of procedures was developed to generate long-term (1850–2005) daily adjusted temperature and precipitation series and to use them to assess changes in climatic extremes. The present report describes details of the data employed to analyze the behavior of Spanish climate extremes and discusses the results of investigations into the annual changes in selected indices that occurred during the 20th century: exceedances of upper and lower percentiles of daily maximum (T_{max}) and minimum (T_{min}) temperatures, cold-spell duration index (CSDI), warm-spell duration index (WSDI), daily rainfall (R) exceeding the 95th and 99th percentiles, simple daily intensity index (SDII), and greatest 1- and 5-day total precipitation. Upper and lower temperature percentiles increased during the 20th century over mainland Spain, but changes in daytime extreme temperatures were larger than changes in night-time extreme temperatures. This pattern, however, shifted slightly in the recent period of strong warming, with more similar rates of change among daytime and night-time extreme temperatures. Changes in extreme precipitation indices were not as evident as those in extreme-temperature indices, but there was a tendency towards heavier precipitation.

Keywords: extreme temperature and precipitation change, daily distribution, temperature- and precipitation-extreme indices, Spain

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Knowledge as to how climatic extremes are changing, during the instrumental period and the recent period of strong (global-scale) warming, is currently an important scientific goal, as climatic extremes have high environmental and socio-economic impacts. Weather extremes (extremely hot or extremely cold days and nights, heavy precipitation, etc.) have numerous negative effects on natural (plant and animal communities, forest fires, soil erosion, etc.) and human (infrastructure damage, human health, water supply, etc.) systems. However, our understanding of current temporal and spatial changes in the occurrence of climatic extremes and our ability to predict their impacts are obstructed by the glaring lack of reliable and long-term daily data at different spatial (from global to local) scales. The limited spatial (fewer records than needed) and temporal (shorter than required) resolution of the available climate records constrains our ability to better understand changes in the extreme state of the climate and its forcing factors. Fortunately, in recent years the climate science community has exerted remarkable effort in providing reliable daily records and in employing them to enhance our knowledge about climatic extremes.

In this regard, the World Meteorological Organization (WMO) Commission for Climatology (CCl)/World Climate Research Programme (WCRP) on Climate Variability and Predictability (CLIVAR)/Joint WMO-Intergovernmental Oceanographic Commission of the United National Educational, Scientific and Cultural Organization (UNESCO) Technical Commission for Oceanography and Marine Meteorology (JCOMM) Expert Team on Climate Change Detection and Indices (ETCCDI) has organized regional workshops and developed a suite of climate-extreme indices, both of which aim to document change in climatic extremes over poorly studied areas [40, 37, 1, 19, 13, 29] and thereby to enhance global analysis [2].

At the European scale, earlier studies analyzing changes in the extreme state of the climate employed daily records to describe and assess trends in extreme temperatures and precipitation, including information for the Spanish sub-region. Moberg et al. [27] widely explored day-to-day temperature variability across Europe, based on 160- to 275-year-long European records, in the framework of the EU project "Improved Understanding of Past Climatic Variability from Early Daily European Instrumental Sources" (IMPROVE). This project made use of the long-term Spanish daily temperature record for Cadiz. Another temperature record of daily maximum and minimum temperature, Barcelona/Fabra station, was studied by Serra et al. [36] for the period 1917–1998. For the second half of the 20th century and for southern Spain, Easterling et al. [10] and Mokssit [28] documented trends in extreme temperatures using measurements made at six Spanish stations as part of a study aimed at estimating extreme-climate indices for Africa. In the framework of the project European Climate Assessment & Dataset project (ECA&D), five daily Spanish temperature records were assessed as part of an analysis of the changes in extreme-climate behavior [17, 18, 16]. By employing daily temperature and precipitation data from ECA&D, which includes measurements obtained from several Spanish stations, Moberg and Jones [25] were able to explore the changes that had occurred over central and western Europe changes during the 20th century based on climate-extreme indices selected from the 64 indices comprising the EMULATE core list (http://www.cru.uea.ac.uk/cru/projects/emulate/ public/).

Specifically for Spain, Romero et al. [34] examined changes in days with rainfall exceeding different thresholds (R >1 mm, R >10 mm, R >25 mm, R >100 mm) as well as the mean duration of wet and dry spells by using a dense network of 410 rain-gauge stations and data for the period 1964–1993. Goodess and Jones [12] analyzed 57 daily Spanish precipitation records for the second half of the 20th century, looking for changes in the characteristics of Iberian daily rainfall and exploring links between large-scale circulation and Iberian precipitation. Occurrences of cold and warm extreme events and their relationships with large-scale atmospheric patterns were examined for Madrid by García-Herrera et al. [11] and Prieto et al. [30]. In addition, Prieto et al. [31] analyzed the health impacts of extremely cold days (T_{min} < 5th percentile) from November to March for the period 1955–1998 over mainland Spain. Rodríguez-Puebla et al. [33] studied changes in summer maximum temperatures ($T_{\max}$ > 90th percentile) over the Iberian Peninsula for the second half of the 20th century by assessing 29 records of daily maximum temperature. Miró et al. [24] monitored daily summer temperatures (July and August) over the Valencia Region (eastern Spain) from 1958 to 2003. Lana et al. [21] examined spatial and temporal patterns in the daily rainfall regime of Catalonia for the second half of the 20th century. Statistical distributions of annual extreme and long dry spells for the Iberian Peninsula were investigated by Lana et al. [20] using a daily database composed of 43 records for 1951–1990. Martinez et al. [23] followed Catalonian daily rainfall distributions during the second half of the 20th century, focusing on several central and upper percentiles and employing a network of 75 rain-gauge stations. Rodrigo and Trigo [32] focused on the Iberian Peninsula in the second half of the 20th century and used data collected from 22 stations to explore annual and seasonal total precipitation, number of wet days, precipitation intensity, and percentage of rain falling on days with rainfall above 95th percentile.

Very recently, Moberg et al. [26] analyzed daily temperature and precipitation extreme changes in Europe for the period 1901–2000 and Della-Marta et al. [8] explored changes in summer heat-wave occurrences over Western Europe for the period 1880–2003. Della-Marta et al. [9] used a homogenized subset of the series from Europe described in Della-Marta et al. [8] and Moberg et al. [26] to document changes in the daily maximum temperature probability density function and the frequency of hot days and heat waves. A complete European trend atlas of the extreme-temperature and extreme-precipitation indices defined in EMULATE was developed by Chen et al. [7] (also available on-line at http://www.gvc2.gu.se/ngeo/rcg/), who also employed EMULATE daily data, which included Iberia as one of the European regions documented. These studies made use of several of the Spanish daily homogenized records developed by Brunet et al. [6].

Despite this backdrop, an insufficient number of studies has explored changes in climatic extremes over areas larger than single localities, analyzed longer periods, or documented changes across the year. Thus, there is still a need to investigate the changes in the extreme states of Spanish climate. In the present study, an analysis of annual changes in temperature and precipitation extremes was carried out by employing some of the available climatic extreme indices developed by the joint CCl/CLIVAR/JCOMM ETCCDI. Both for temperature and precipitation data, percentile-based indices were explored, together with duration indices and other indicators. For temperature, upper and lower percentiles, and for precipitation, upper percentiles were analyzed, together with the WSDI and CSDI. For precipitation, SDII and greatest 1-and 5-day total rainfall were determined as well.

This article is organized as follows: the data, selected indices, and analytical procedures are described in the following section. Them, the other sections are devoted to an assessment of changes in temperature extreme indices over mainland Spain, and document changes in precipitation extreme indices. The last section summarizes the results.

Data, indices, and analytical techniques

In the framework of the European Community (EC)-funded project EMULATE (**E**uropean and North Atlantic daily to **MUL**ti-decadal Clim**ATE** variability[1]), we selected the 22 longest, most complete, and most reliable daily Spanish temperature and precipitation records extending back to the mid-19th century. Table 1 shows the network details (station names, geo-

Table 1. The Spanish temperature and precipitation network. Name of station, current geographical location (geographical coordinates and elevation), and length of record

Location	*Long*	*Lat*	*Alt (m)*	*Length*
Alacant	00° 29’ 40” W	38° 22’ 00” N	81	1893–2005
Albacete	01° 51’ 47” W	38° 57’ 08” N	699	1893–2005
Badajoz	06° 49’ 45” W	38° 53’ 00” N	185	1864–2005
Barcelona	02° 10’ 36” E	41° 25’ 05” N	420	1885–2005
Burgos	03° 36’ 57’’ W	42° 21’ 22” N	881	1870–2005
Cadiz	06° 12’ 37” W	36° 27’ 55” N	30	1850–2005
Ciudad Real	03° 55’ 11” W	38° 59’ 22” N	627	1893–2005
Granada	03° 37’ 52” W	37° 08’ 10” N	685	1893–2005
Huelva	06° 54’ 35” W	37° 16’ 48” N	19	1903–2005
Huesca	00° 19’ 35” W	42° 05’ 00’’ N	541	1861–2005
La Coruña	08° 25’ 10’’ W	43° 22’ 02’’ N	67	1882–2005
Madrid	03° 40’ 41” W	40° 24’ 40” N	679	1853–2005
Malaga	04° 28’ 57” W	36° 39’ 57” N	6	1893–2005
Murcia	01° 07’ 14” W	37° 58’ 59” N	57	1863–2005
Pamplona	01° 38’ 21’’ W	42° 46’ 06” N	452	1880–2005
Salamanca	05° 29’ 41” W	40° 56’ 50” N	789	1893–2005
San Sebastian	02° 02’ 22’’ W	43° 18’ 24’’ N	251	1893–2005
Sevilla	05° 53’ 47” W	37° 25’ 15” N	31	1893–2005
Soria	02° 29’ 01” W	41° 46’ 29” N	1083	1893–2005
Valencia	00° 22’ 52” W	39° 28’ 48” N	11	1864–2005
Valladolid	04° 44’ 35” W	41° 38’40” N	691	1893–2005
Zaragoza	01° 00’ 29’’ W	41° 39’ 43” N	245	1887–2005

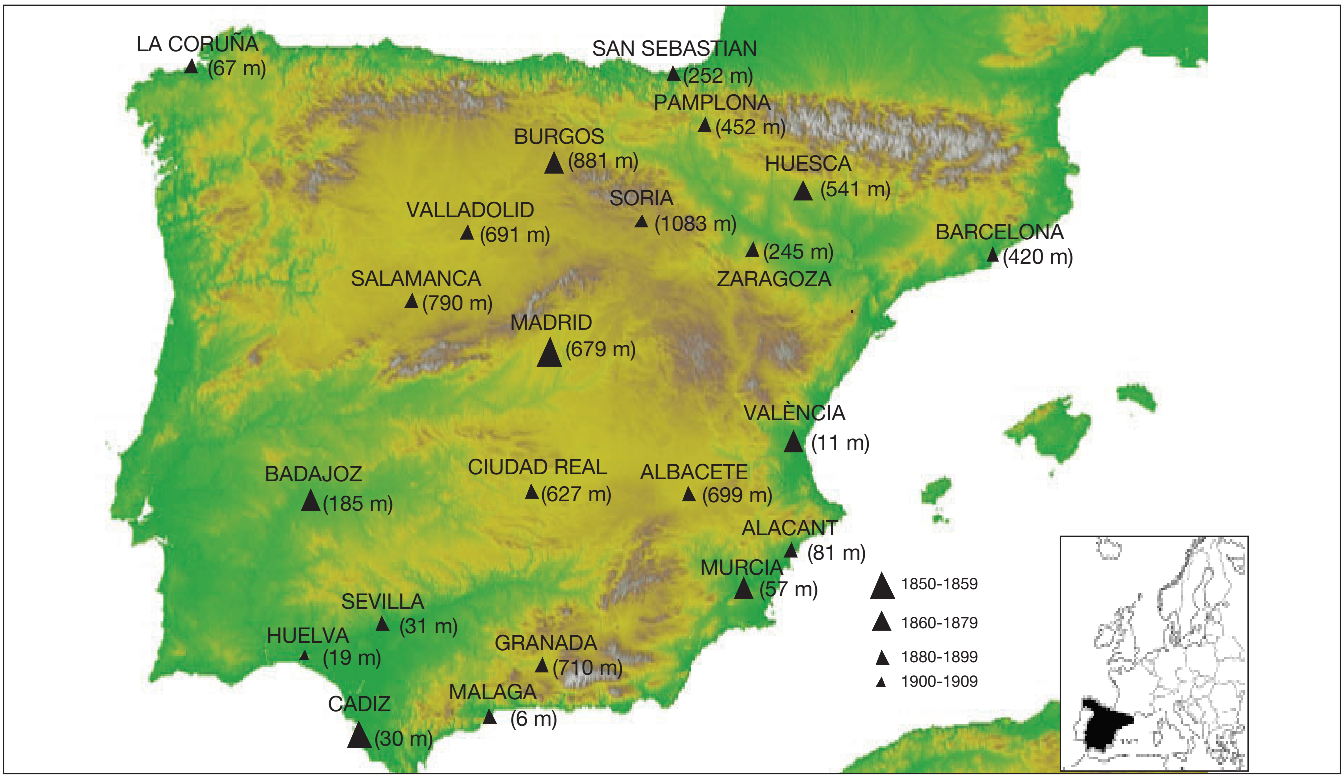

Figure 1. Map showing the locations of the measurement stations. The approximate lengths of the temperature and precipitation records are also indicated.

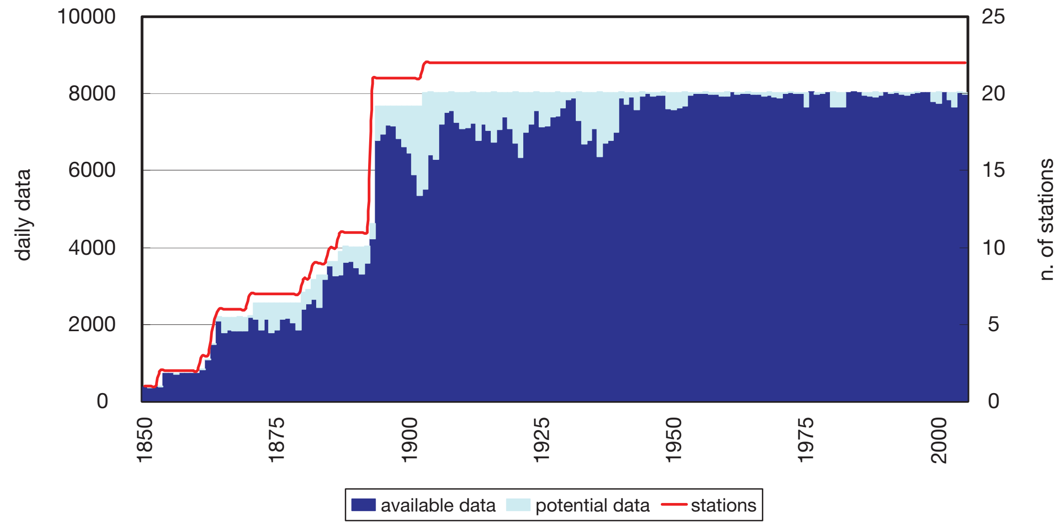

Figure 2. Available vs. potential daily data (*left axis*) and the number of meteorological stations (*right axis*).

Table 2. Temperature– and precipitation-extreme indices employed in this study, together with their identifiers, parameter description, definitions, and units for each index. TX, daily maximum temperature; TN, daily minimum temperature; R, precipitation. Indices were annually resolved by employing RClimDex software. Annual values were calculated from January to December

Identifier	*Parameter definition*	*Indices description*	*Units*
TX2p	> T_{max} 2nd percentile	Extremely cold days	% days
TX5p	> T_{max} 5th percentile	Very cold days	% days
TX10p	> T_{max} 10th percentile	Cold days	% days
TX90p	> T_{max} 90th percentile	Hot days	% days
TX95p	> T_{max} 95th percentile	Very hot days	% days
TX98p	> T_{max} 98th percentile	Extremely hot days	% days
TN2p	> T_{min} 2nd percentile	Extremely cold nights	% days
TN5p	> T_{min} 5th percentile	Very cold nights	% days
TN10p	> T_{min} 10th percentile	Cold nights	% days
TN90p	> T_{min} 90th percentile	Hot nights	% days
TN95p	> T_{min} 95th percentile	Very hot nights	% days
TN98p	> T_{min} 98th percentile	Extremely hot nights	% days
WSDI	Counts of days with at least 6 consecutive days when T_{max} > 90th	Warm-spell duration index	days
CSDI	Counts of days with at least 6 consecutive days when T_{min} < 10th	Cold-spell duration index	days
R1d	Greatest 1-day total rainfall	Maximum one wet day	mm
R5d	Greatest 5-day total rainfall	Maximum five wet days	mm
SDII	Total annual rainfall divided by the number of wet days (R ≥ 0.1 mm)	Simple daily intensity index	mm/day
R95p	Total annual R >95th percentile	Very wet days	mm
R99p	Total annual R >99th percentile	Extremely wet days	mm

graphical coordinates, elevations, and length of records) and Fig. 1 depicts the locations of the Spanish network. Although the bulk of these data were obtained in digital and hard-copy form from the Instituto Nacional de Meteorología (INM, Spanish Meteorological Office), a number of other sources of meteorological information were used in this study, particularly for the 19th century. Details of the sources and record combination can be found in Table III of [6]. As an example, Fig. 2 shows the available daily mean temperature data with respect to the potential recorded daily data (left axis) and the number of stations (right axis) throughout the period 1850–2005.

The network covered the entire country reasonably well, encompassing the main Spanish climate types (Oceanic and Mediterranean) and sub-types (Atlantic, 2; Continental, 10; Eastern Mediterranean coast, 2; Southern, 6; and Southeastern, 2 stations) according to the Spanish climate classification of Martin-Vide and Olcina [22].

Raw daily T_{max} and T_{min} and daily precipitation were subjected to different quality-control (QC) tests to identify and flag major errors of digitization as well as to ensure internal consistency, temporal coherence, and spatial coherence of the data. Checks of gross errors (aberrant values, problems with decimal points, calendar dates, negative precipitation, etc.), T_{max} < T_{min} values, consecutive values repeating at least four times, temperature (precipitation) values greater than ± 4 (± 6) standard deviations of the threshold for both the candidate record and its group of reference stations, and values exceeding the expected amount of change were exhaustively assessed in the raw data. More detailed information on both the applied QC and the results for the temperature data are shown and discussed in [6].

A relative homogeneity reassessment of the monthly averaged data, based on the standard normal homogeneity test (SNHT) developed by Alexandersson and Moberg [3], was then applied to the previously adjusted (for screen bias) and updated to 2005 temperature records. Details on minimization of "screen bias" from monthly temperature raw data are provided in Brunet et al. [4, 5]. To interpolate monthly correction factors to a daily basis, a scheme similar to that used by Vincent et al. [38] was followed. Complete details on the procedures to adjust maximum and minimum daily data are provided in Brunet et al. [4], where the procedures for developing daily adjusted datasets are also available.

Long-term changes in extreme temperatures and precipitation were studied in order to document important changes in the occurrence of climatic extremes for mainland Spain over the entire 20th century and to identify changes in the probability density function of Spanish temperature and precipitation records, with special emphasis on the recent period of accelerated warming. This aim was achieved by employing, on an annual basis, several of the 27 core indices developed by the ETCCDI and the RClimDex software package [39]. The 2nd, 5th, 95th, and 98th percentiles were added to this study to further explore the tails of the $T_{\max}$ and T_{min} distributions. The suite of indices and the software package are available from http://cccma.seos.uvic.ca/ETCCDMI/. Table 2 lists the climatic-extreme indices employed in the analysis, together with details of identifiers, parameter definition, indices description, and units employed for each extreme index.

Indices of relevant parameters were generated on a station basis and then averaged together following the simple weighting algorithm described by Jones and Hulme [14]. This allowed regional time series representative of the whole of mainland Spain to be developed for climate-extreme behavior.

Long-term changes in climatic extremes were explored by aiming to identify time variations and trends over the entire 20th century as well as the different sub-periods of rising and falling temperatures identified by Brunet et al. [5]. Here, temporal variations of the climate extremes indices were highlighted by employing a Gaussian low-pass filter of 13 terms in order to suppress high-frequency fluctuations on time scales less than decadal. The filter has six weights on either side of a central weight (for a total of 13). To extend the smoothed series to the starts/ends of the series, additional values (equal to the average of the last/first 6 years) were added. Climate-extreme change explained by a robust linear trend was shown to fit over the entire period. In addition, several sub-periods of rising and falling temperatures were calculated on an annual basis by adapting the slope estimator of Sen [35]. All trends were tested for statistical significance at the 0.01 level unless otherwise stated. The 95% confidence intervals of trend coefficients were also estimated from tabulated values [15] and are provided in the text.

Temporal changes in temperature-extreme indices

The annual time series of Spanish area-averaged frequency of days exceeding the 2nd, 5th, 10th, 90th, 95th, and 98th percentiles of $T_{\max}$ and T_{min} are shown in Fig. 3. The top (bottom) panel shows variations of the $T_{\max}$ and T_{min} upper (lower) percentiles. Table 3 shows the rates of change per decade in the percentile-based temperature and precipitation extremes, other indices for the 1901–2005 period, and the sub-periods of rising and falling temperatures over mainland Spain: the initial warming episode (1901–1949), the intermediate cooling episode (1950–1972), and the recent episode of accelerated warming (from 1973 onwards).

In Fig. 3, the lower (2nd, 5th, and 10th) percentiles of the daily $T_{\max}$ (T_{min}) distributions indicate days (nights) representing cold, very cold, and extremely cold events, while the upper (90th, 95th, and 98th) percentiles designate hot, very hot, and extremely hot days (nights).

Changes in the distributions of daily $T_{\max}$ and T_{min} across the 20th century show a warming shift affecting the lower and upper tails of both distributions, with a particularly remarkable increase since 1973. Both tails of $T_{\max}$ warmed at similar rates of change across the 20th century and, although the lower and upper tails of T_{min} also warmed at comparable rates, this was less intense than the $T_{\max}$ indices during the entire period. In this regard, Spanish warming in the 20th century, first identified by Brunet et al. [5], was more the result of faster reductions (increases) of daytime cold (hot) extreme indices than night-time reductions (increases) of cold (hot) extreme events. The tails of the $T_{\max}$ and T_{min} daily distributions warmed, but the $T_{\max}$ tails warmed faster than the T_{min} tails.

In the initial episode of warming, statistically significant trends were estimated only for daytime-extreme indices (lower and upper percentiles of $T_{\max}$), which indicated that this warming was strongly induced by higher increases in daytime than in night-time (both lower and upper percentiles of T_{min}) extreme temperatures. The cooling episode (1950–1972) was associated with increases (reductions) in cold to extremely cold days (hot to extremely hot nights), although no trend coefficient reached statistical significance. The fastest rates of Spanish temperature-extreme changes in the 20th century occurred during the recent period (1973–2005) of strong warming, which makes this period the most striking feature of the 20th century Spanish warming and at the same time indicates that Spanish warming has become more extreme. The upper (lower) tails of night-time and daytime temperatures had the highest rates of positive (negative) change. This was due to the slightly higher trends estimated for T_{min} than for $T_{\max}$ indices, showing a shift in observed Spanish warming during the 20th century. This finding indicates that hot to very extremely hot (cold to extremely cold) nights have become slightly more (less) frequent extreme events than daytime temperature extremes.

In order to assess whether the difference in the rates of change among upper and lower percentile indices with respect to their temporal evolution was due simply to having fewer total observations exceeding the higher thresholds (95th and 98th percentiles compared to the 90th percentile) and the lower thresholds (2nd and 5th compared to the 10th percentile), the time series were normalized by dividing them by their standard deviations. As an example, exploration of the normalized time series of $T_{\max}$ lower percentiles and T_{min} upper percentiles, shown in Fig. 4 (top and bottom, respectively), revealed that the changes in the upper T_{min} and lower $T_{\max}$ percentile exceedances were almost identical when examined on a normalized basis.

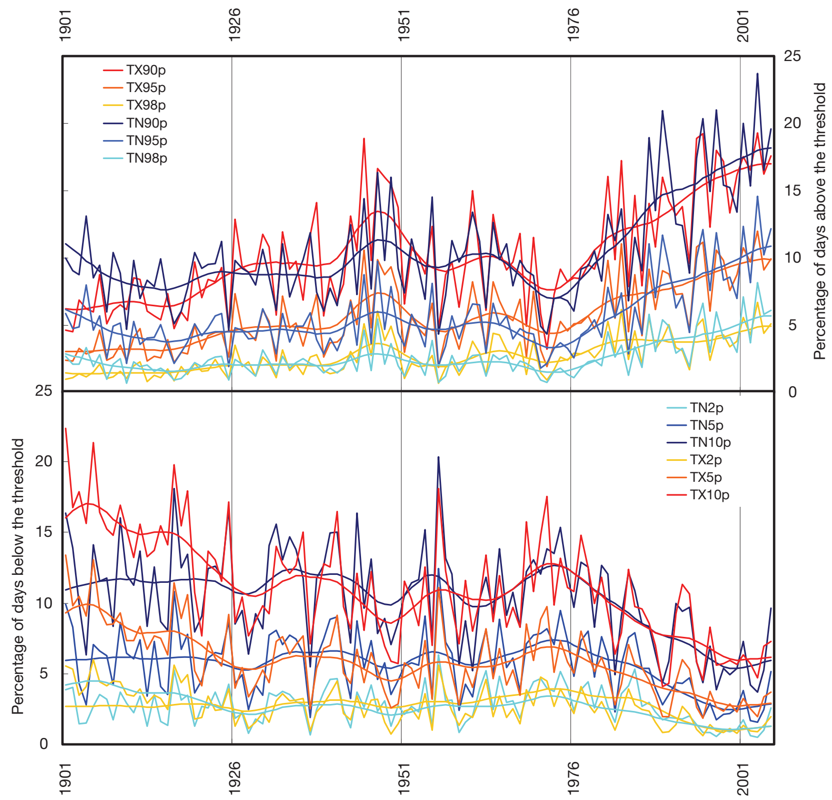

Figure 3. Annual time series of daily T_{max} and T_{min} upper (*top*) and lower (*bottom*) percentile-based extreme indices, expressed as percentage of days above (below) the indicated threshold and filtered by a low-pass Gaussian filter (see text for details). Note that hot, extremely hot, and very extremely hot nights became more frequent than daytime upper tails during the last period of warming, in contrast to the long-term evolution of daytime and night-time extreme indices. Also note the larger reductions in the T_{max} 10th and 5th extreme indices throughout the 20th century.

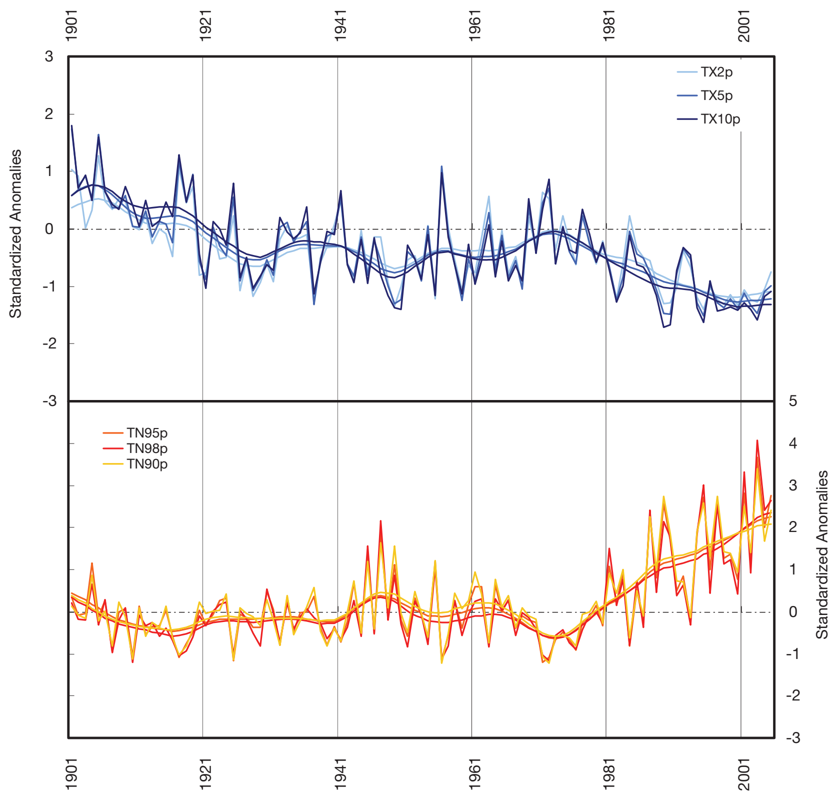

Figure 4. Standardized annual anomaly time series of percentage of days exceeding the lower percentiles of daily maximum temperatures (*top*) and upper percentiles of daily minimum temperatures (*bottom*), smoothed by a Gaussian filter of 13 terms.

Table 3. Annual temperature and precipitation change per decade as fitted by a robust linear trend. The associated ± standard errors for the 95% confidence interval of the extreme temperature indices estimated over the entire period and during several episodes of warming and cooling are shown in parentheses. Bold (italic) indicates significance at 0.01 (0.05) levels

Indices	*1901–2005*	*1901–1949*	*1950–1972*	*1973–2005*
Tx2p	**-0.23** (-0.31/-0.16)	**-0.53** (-0.77/-0.30)	0.67 (-0.24/1.39)	**-0.70** (-0.96/-0.44)
Tx5p	**-0.51** (-0.63/-0.38)	**-1.15** (-1.64/-0.76)	1.33 (-0.41/2.61)	**-1.21** (-1.73/-0.74)
Tx10p	**-0.85** (-1.05/-0.66)	**-1.89** (-2.47/-1.27)	1.70 (-0.69/3.63)	**-2.04** (-2.89/-1.22)
Tx90p	**0.83** (0.61/1.05)	**1.51** (0.97/2.10)	-0.76 (-3.35/1.37)	**3.11** (2.09/3.97)
Tx95p	**0.54** (0.41/0.68)	**0.80** (0.49/1.25)	0.07 (-1.47/1.68)	**1.78** (1.05/2.55)
Tx98p	**0.28** (0.22/0.35)	**0.38** (0.20/0.55)	0.27 (-0.59/1.19)	**0.68** (0.29/1.11)
Tn2p	-0.09 (-0.17/0.00)	0.00 (-0.24/0.25)	0.66 (-0.23/1.65)	**-1.15** (-1.48/-0.84)
Tn5p	**-0.26** (-0.40/-0.11)	-0.10 (-0.55/0.39)	1.10 (-0.53/2.44)	**-1.84** (-2.40/-1.22)
Tn10p	**-0.51** (-0.72/-0.30)	-0.25 (-0.95/0.48)	0.75 (-1.59/2.94)	**-2.70** (-3.55/-1.83)
Tn90p	**0.59** (0.36/0.84)	0.25 (-0.24/0.82)	-1.00 (-3.02/1.02)	**3.74** (2.60/5.18)
Tn95p	**0.32** (0.18/0.48)	0.07 (-0.25/0.46)	-0.56 (-1.66/0.70)	**2.52** (1.80/3.50)
Tn98p	**0.16** (0.09/0.24)	0.05 (-0.11/0.22)	-0.10 (-0.80/0.34)	**1.34** (0.80/1.97)
CSDI	**-0.48** (-0.73/-0.24)	0.32 (-0.61/1.23)	*-2.23* (-4.05/-0.26)	-0.78 (-1.95/0.38)
WSDI	**0.44** (0.14/0.77)	**1.36** (0.57/2.36)	-1.48 (-5.13/0.57)	**3.96** (2.26/5.66)
SDII	0.03 (0.00/0.07)	0.09 (-0.02/0.19)	-0.01 (-0.28/0.21)	-0.05 (-0.28/0.17)
R95p	*2.25* (0.45/4.18)	*5.80* (0.35/11.03)	5.63 (-15.61/23.85)	-0.44 (-10.52/10.46)
R99p	**2.13** (0.93/3.34)	**4.67** (1.17/7.64)	5.94 (-4.59/16.14)	0.16 (-5.90/9.81)
R1d	0.27 (-0.12/0.71)	0.96 (-0.29/2.15)	-1.81 (-6.68/1.70)	0.05 (-2.60/2.37)
R5d	**1.20** (0.49/1.80)	**2.81** (1.46/4.46)	1.12 (-6.06/9.64)	0.54 (-3.17/4.78)

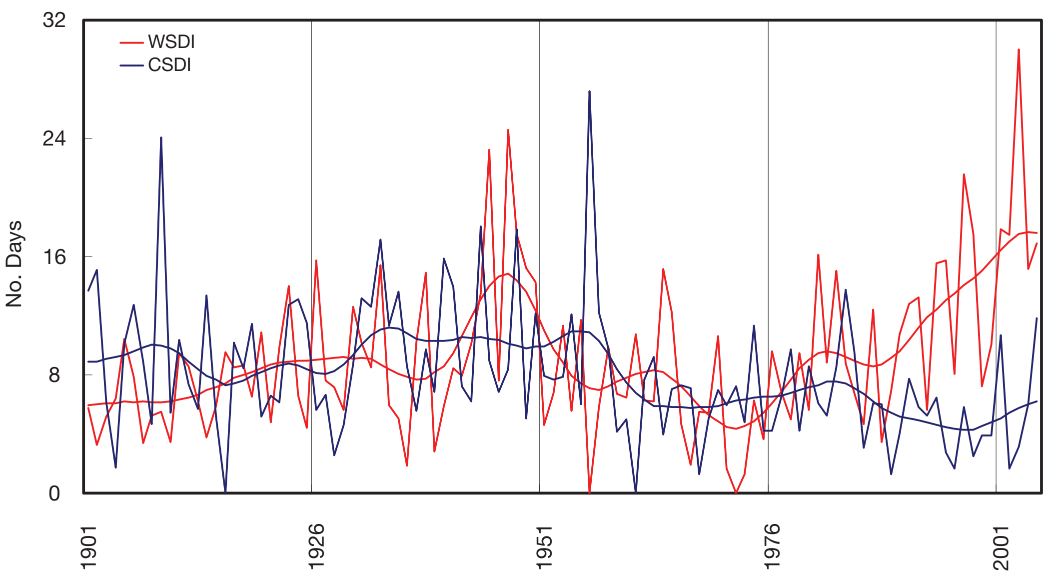

Figure 5. Annual counts of the warm-spell and cold-spell duration indices (WSDI and CSDI) averaged for mainland Spain. Data are expressed as number of days exceeding at least 6 consecutive days when $T_{max} > 90^{th}$ percentile and $T_{min} < 10^{th}$ percentiles, respectively, and were smoothed with a Gaussian filter of 13 terms.

Annual counts of days with at least six consecutive days above the 90th percentile of T_{max} (WSDI) and below the 10th percentile of T_{min} (CSDI) are shown in Fig. 5 and their trends are compiled in Table 3. Both indices can be used as proxies for exploring changes in the length of heat waves and cold outbreaks across the year.

An examination of the changes over the 20th century showed that reductions in the annual frequency of CSDI were slightly larger than the increases in WSDI, which indicated that the reduction of occurrences of cold spells was a more dominant feature of Spanish warming over the entire period. In this regard, it can be stated that 20th century Spanish warming was accompanied by faster reductions of cold outbreaks than of heat waves. However, a remarkable increase in the occurrence of heat waves was the prominent feature observed during the last episode of warming. This points to the fact that the most recent Spanish warming period was characterized by temperatures becoming hotter rather than less cold. Additionally, for the initial period of warming, only WSDI reached significance, which also indicated that Spanish episodes of warming were more related to increases in warm-spell duration indices than to reductions in the lengths of cold spells. Finally, the cooling episode was more influenced by reductions in the occurrence of heat waves than by increases in cold outbreaks, as the number of cold spells was reduced but hardly contributed to the observed cooling.

Temporal changes in indices of Spanish precipitation extremes

Several precipitation indices from the ETCCDI's core list were chosen and analyzed in order to track changes in rainfall intensity over mainland Spain. Figure 6 shows the SDII, which reflects annual intensities of daily rainfall, defined as the total annual rainfall divided by the number of wet days ($R \geq 1$ mm). Table 3 lists the rates of change for the different periods examined. An increase (reduction) in this index indicates that on those days when it rained, the rainfall tended to be heavier (lighter). From an examination of Fig. 6 and Table 3, it can be seen that there were no significant changes at the adopted 0.05 significance level during the 20th century, even though the slight increase estimated for the entire period (1901–2005) was significant at the 0.10 level. This increase was mainly due to the increase in daily intensity observed during the initial episode of warming, at a rate that was significant only at the 0.10 level. However, and in contrast to the second half of the 20th century, Spanish rainfall intensity tended to diminish, particularly during the recent period of abrupt warming, although no trend coefficient reached statistical significance.

Figure 7 shows the temporal variations of annual rainfall from heavy precipitation events (very wet days: days with precipitation equal to or greater than the 95th percentile; extremely wet days: days with precipitation equal to or greater than the 99th percentile). Table 3 lists the estimated trends for several periods. For the entire 20th century, both very wet days and extremely wet days increased significantly, at the 0.05 level in the case of very wet events (Table 3). Therefore, significant increases of heavy precipitation events accompanied Spanish warming in the 20th century, which is consistent with a warming world and observations that heavy precipitation events have been more extreme. Nevertheless, these increases in very wet and extremely wet days were mainly influenced by the larger increments estimated for the initial period of warming, as no change was observed for either measure in the intermediate cold episode or in the recent period of accelerated warming.

Figure 8 shows the highest 1-day and 5-day total rainfall (R1d and R5d, respectively) and Table 3 their estimated trends for several periods. Of the two indices, significant trends over the entire period were estimated only for R5d. Again, this increasing trend was mainly associated with the initial episode of warming, while that in the second half of the 20th century did not reach statistical significance. The highest 1-day total rainfall index was not statistically significant, although the estimated trends suggest positive rates of change, except during the cold episode.

Thus, regarding the precipitation indices, daily rainfall intensity and heavy precipitation events increased, over the 20th century, consistent with a warmer climate. However, for the recent period of accelerated warming, no significant changes in the precipitation-extreme indices were estimated.

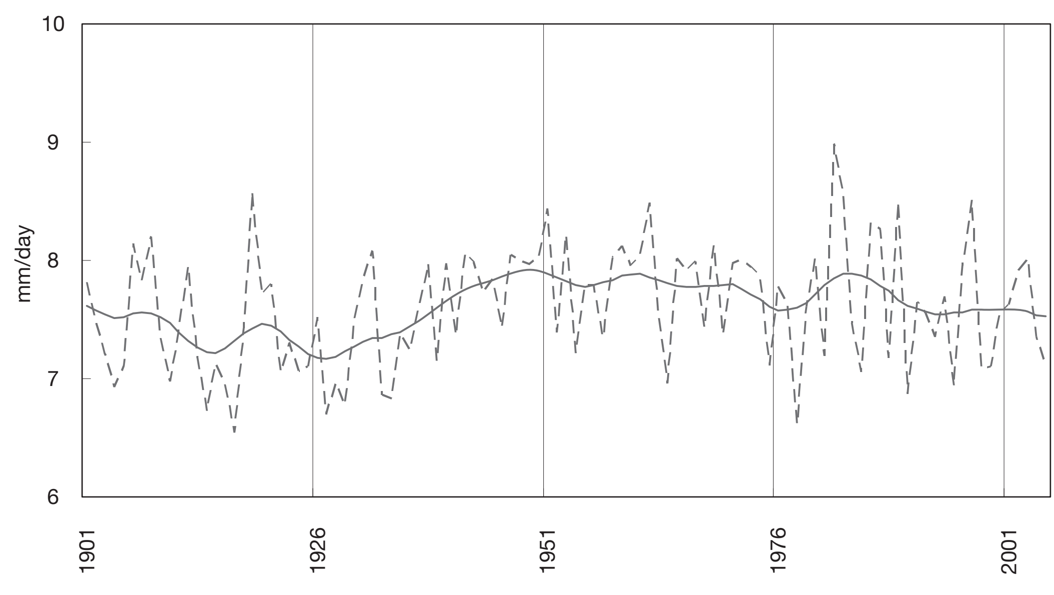

Figure 6. Annual time series of the simple daily intensity index (*dashed line*) area-averaged over mainland Spain and smoothed by a Gaussian filter of 13 terms (*solid line*).

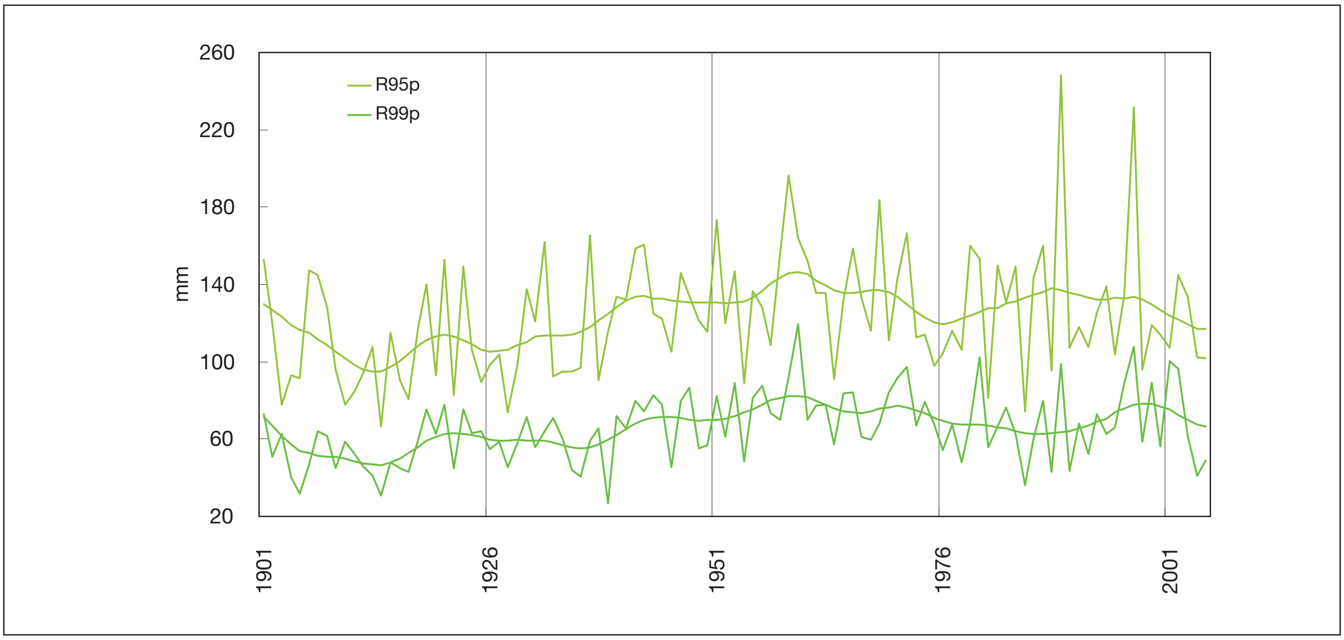

Figure 7. Spanish area-averaged annual time series (in mm) of very wet days (rainfall exceeding the 95th percentile) and extremely wet days (rainfall exceeding the 99th percentile), smoothed by a Gaussian filter of 13 terms.

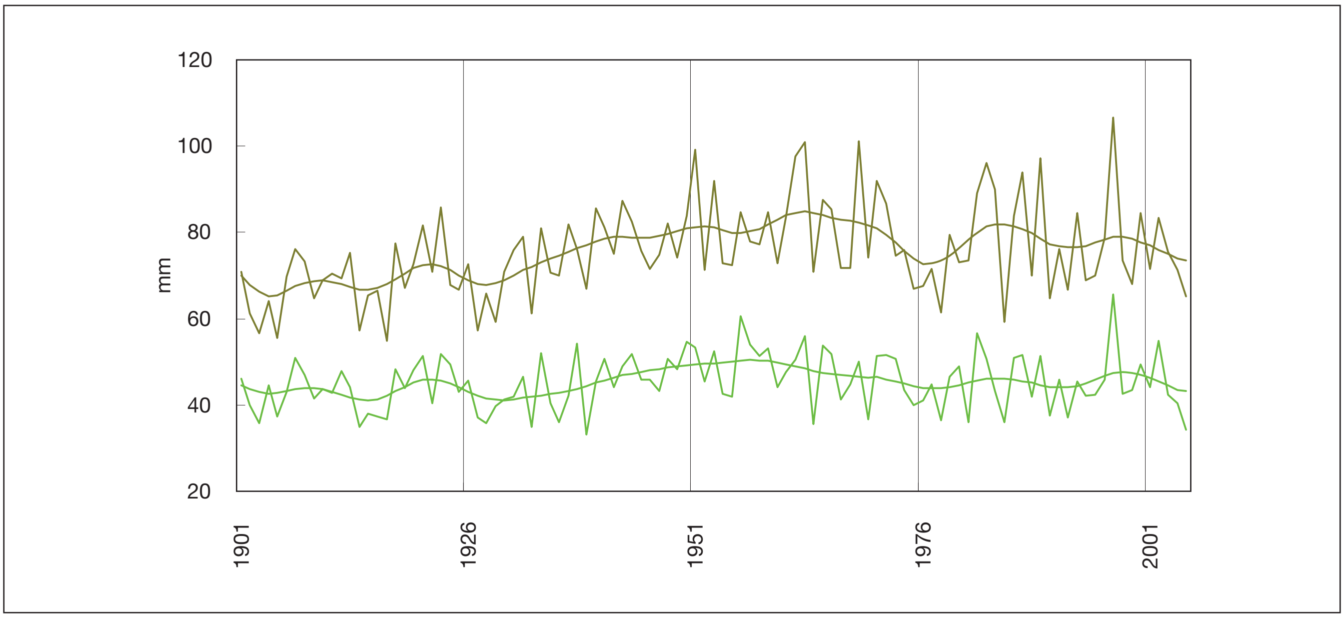

Figure 8. Spanish area-averaged annual time series of greatest 1-day (*bottom light-green lines*) and 5-day (*top dark-green lines*) total rainfall, smoothed by a Gaussian filter of 13 terms.

Summary and conclusions

New daily adjusted datasets of maximum and minimum temperatures and precipitation have enabled changes in climatic extremes over peninsular Spain during the 20th century to be assessed by using the climatic-extreme indices developed by the joint CCI/CLIVAR/JCOMM ETCCDI. Annual variations and trends of these indices showed increases (reductions) of the upper (lower) percentiles of the daily maximum and minimum temperatures. Both the upper and the lower tails of T_{max} and T_{min} series warmed by about the same magnitude when compared with each other, but the rates of change for the upper and lower percentiles of T_{max} were larger than those estimated for T_{min} percentile indices over the entire period. Nevertheless, during the recent period of strong warming (since 1973), warming of the T_{min} tails accelerated, such that the contributions to the estimated recent warming of the daily variables and their percentile-based indices were similar. Cold (warm) spells decreased (increased) throughout the 20th century, but during the recent period of warming warm spells increased in duration at rates higher than those of cold spells. All measures employed to assess changes in extreme Spanish precipitation indicated a tendency towards more intense rainy days and increases in heavy precipitation during the 20th century–a behavior consistent with a warmer planet. However, these changes were not evenly spread throughout the entire analyzed period. Indeed, they were mostly the result of increases that occurred during the initial episode of warming (first half of the 20th century), whereas no significant changes in precipitation extreme indices were detected during the last period of strong warming.

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